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XI.

ON THE VARIATIONS OF THE "HALL EFFECT" IN
SEVERAL METALS WITH CHANGES OF
TEMPERATURE.

BY ALBERT L. CLOUGH AND EDWIN H. HALL.

Presented April 12, 1893.

THE variation of the so called "Hall effect" with change of temperature in the magnetic metals has long been known. In 1885 the following estimate was given:—

"A fall of 1° C. in temperature causes in the R. P. [rotational power] of Iron		a fall of $\frac{2}{3}\%$ approx.	
Steel, soft,	"	$\frac{1}{3}$	"
" tempered,	"	$\frac{1}{3}$	"
Cobalt	"	1	"
Nickel	"	$\frac{2}{3}$	"
Non-magnetic metals, apparently a small increase."*			

The evidence in favor of an increase with fall of temperature in non-magnetic metals was very slight.

Leduc† has more recently studied the temperature change in bismuth.

The Hall effect shows itself in the form of an electromotive force, brought about by magnetic action, at right angles with the lines of flow of an electric current. It is evident that under such conditions the equipotential lines are no longer at right angles with the lines of flow, as they are when the magnetic force is not operating. This fact gives rise to the terms "rotational power" and "rotational coefficient," which have been used in describing the phenomena under discussion. These terms are somewhat ambiguous, for the reason that they may with as much propriety be used in connection with the rotation of the plane of polarization of light.

* E. H. Hall, Amer. Journ. of Sci., February, 1885, p. 133.

† La Lumière Electrique, Vol. XXIX., 1888.

The existence of a transverse electromotive force under the conditions described might be accounted for in either of two general ways: 1st. The combined action of the main electric current and the magnetic force might be supposed to produce in the conductor a state of strain, giving it for the time being properties similar to those possessed by certain crystals, which do not conduct equally well in all directions. This might be called the *static* theory of the phenomenon, and one adopting it would expect the transverse effect to increase or decrease with the electric resistance of the conductor, that is, he would expect to see a fall of temperature accompanied by a diminution of the transverse effect, and *vice versa*. 2d. The transverse electromotive force might be regarded as the result of molecular or cellular motions, probably rotations, set up within the conductor by the magnetic force, and acting upon the main current of electricity in such a manner as to produce a *tendency* to deflection. This might be called the *kinetic* theory, and one holding it need not be surprised to find the transverse electromotive force independent of those temperature changes which affect electric resistance.

As most observations upon the temperature changes of the Hall effect had been confined to narrow limits, between 30° C. and 0° C., it seemed important to undertake a serious and extended investigation reaching through a much greater range of temperatures. This investigation is by no means completed, but some results of interest have already been attained. Most of the experimental work leading to these results was done by Mr. A. L. Clough, a graduate student, in the Jefferson Physical Laboratory of Harvard College during the academic year 1891-'92.

The substances used were, especially, soft cold-rolled steel and soft rolled nickel, but some few observations were made with carbon, copper, and phosphor-bronze. The general method of the experiments was similar to that which Professor Hall had used in previous investigations. The most important variations, which will presently be described, were those required by the use of high temperatures. The substances examined, with the exception of carbon, were in the usual shape of thin strips several centimeters long and about one centimeter wide, with narrow arms projecting at right angles with the sides. None of the work lays claim to great numerical exactness. It is a pioneer exploration rather than an accurate survey.

In some observations at moderate temperatures the same narrow water bath was used that was described in the American Journal of Science, Vol. XXIX. p. 118. A hot-air bath was used for tempera-

tures above the range of this device. It was formed of a narrow brass chamber arranged to be placed conveniently between the magnet poles. It was furnished with a funnel-shaped pipe extending downward, under which could be set a Bunsen gas-burner, and it was surmounted by a brass chimney to carry off the products of combustion. The height of the flame of the burner could be regulated so as to furnish any required amount of heated air, which circulated uniformly past the specimen to be examined. By shielding the gas flame from air currents and jacketing the outside of the bath with asbestos cloth a tolerably uniform temperature was attained. A high range thermometer was inserted into the air bath, with its bulb in close proximity to the specimen.

In many cases the change of electrical resistance with change of temperature was noted by means of observations on the magnitude of the difference of potential between the admission and exit ends of the strip under examination. These observations served to show directly that in nickel and steel at ordinary temperatures the temperature coefficient of the Hall effect is greater than the temperature coefficient of the electrical resistance.

The numbers given in this paper are, in most cases, not those actually observed, but have been derived from the actual observations by changes, usually slight, intended to make allowance for certain variations in the conditions of the experiments, such as fluctuations of the magnetic force or of the main current in the strip. The results reached with the various substances examined will now be given.

COPPER.

From a sheet of thin commercial copper about 0.01 cm. in thickness an experimental strip was cut, which had the usual form with the exception that the side arms were made very long in order that their junctions with the galvanometer wires might lie outside the air-bath. In the table that follows, the first column, t , gives the temperature in degrees Centigrade; the second column, a , the reading of the instrument used to measure the magnetizing current; the third, θ , the readings of the tangent galvanometer used to measure the primary current through the copper strip; the fourth, H , the Hall effect deflections of the mirror galvanometer.

t	a	θ	H
°		°	
23	36.9	66.8	3.2
210	36.3	66.4	2.9
Above 360	36.5	66.3	3.1

These observations show that no large change in the Hall effect is produced in copper by a rise of more than 300° , and leave it an open question whether any change is produced.

PHOSPHOR-BRONZE.

The Hall effect in a strip of this substance was about one half as large as in the copper just described, the thickness of the two strips being nearly the same. Mr. Clough found no increase of this effect in raising the temperature from 20° to 360° . He found the temperature coefficient of the electrical resistance of the specimen examined to be about .00045.

COLD-ROLLED STEEL.

A number of strips of this substance, about 0.016 cm. thick, mounted or supported in various ways, were tested. For satisfactory results at high temperatures it was found necessary to make the side branches long enough to extend outside the air bath. Otherwise very troublesome thermo-electric effects were likely to occur at the junctions with the wires leading to the mirror galvanometer. The following table gives, in divisions of the galvanometer scale, the results of the series of observations that ran through the widest range of temperature.

t °	H.
18	5.26
116	15.0
199	27.2
263	39.5
319	49.0

The second column assumes a constant value of the primary current in the strip, and a constant value, about 1400 c. g. s., for the strength of the magnetic field and for the magnetic induction per square centimeter through the steel.

Curve A in Figure 1 is plotted to correspond with the quantities just given, the abscissas representing temperatures and the ordinates values of the Hall effect. For comparison, curve *a*, Figure 1, is intended to show the relation of temperature to magnetic permeability in "Whitworth mild steel," with a constant value, 1500, for the magnetic induction per square centimeter through it. This curve is plotted from data obtained from curves given by Dr. John Hopkinson in the Transactions of the Royal Society for 1889. It will be seen that the permeability curve of the Whitworth steel is concave upward, even

at very high temperatures, while the Hall effect curve, *as here given*, for French cold rolled steel begins to diminish in steepness in the region of 300°C . The data for the latter curve, however, are too inaccurate to warrant attaching much importance to this feature. It is very likely that the true curve would continue to increase in steepness far beyond the point corresponding to 300°C . It is evident that, until very high temperatures are reached, the Hall effect in French cold-rolled steel increases much more rapidly with rise of temperature than the permeability of Whitworth steel does.

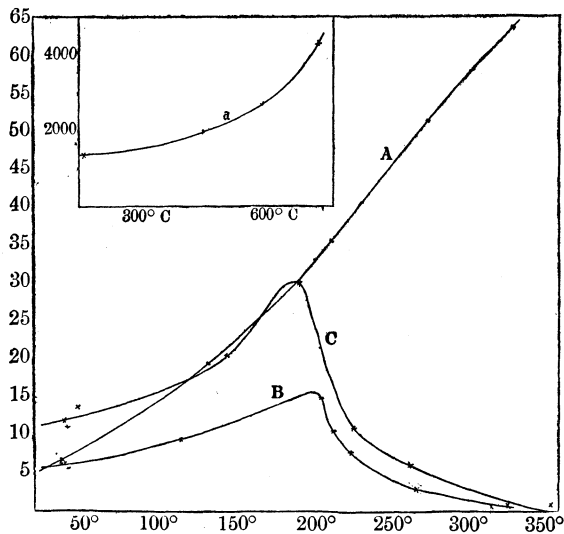


FIGURE 1.

NICKEL.

This was from a sheet of rolled nickel from Wharton, Philadelphia, and was probably very pure. It was about 0.033 cm. thick. The sheet from which it was cut was not large enough to allow of making the original side arms of the strip very long, but they were pieced out with shreds from the nickel sheet, so that the junctions of nickel with the copper wires lay outside the air bath. The shreds of nickel were fastened to the arms of the strip by means of screw-clamps, and these clamps were insulated from the nickel by pieces of mica. At times the device of wrapping the nickel strip in asbestos paper was tried as a means of preventing sudden fluctuations of temperature. In spite

of all precautions, however, there were large thermo-electric effects. Sometimes these effects were sufficiently large and sufficiently constant to carry the index of the mirror galvanometer completely off the scale and hold it there. In such cases a compensating arrangement was resorted to, which consisted of a short wire inserted in the galvanometer circuit, which wire formed also part of another circuit containing a Daniell cell and a variable resistance. This arrangement tended to send through the galvanometer a small current, which was made to oppose and nearly neutralize the thermo-electric current from the nickel strip. There were, nevertheless, serious fluctuations of the galvanometer index when high temperatures were used, and at the highest temperatures, where, it will be observed, the Hall effect in nickel was very small, it was necessary to take a long series of readings in order to obtain a result even approximately satisfactory. The following table shows the results arrived at, the Hall effects being expressed as before, in divisions of the galvanometer scale.

STRENGTH OF FIELD = 1,500 c g s.			STRENGTH OF FIELD = 3,000 c. g. s		
Date.	t °C.	H.	Date.	t °C.	H.
April 27, 1892	18	6.2	May 10, 1892	20	12.0
May 6, "	22	5.8	" 12, "	22	11.1
" 6, "	98	9.5	" 12, "	128	20.4
" 6, "	192	14.9	" 12, "	213	11.0
" 7, "	22	6.2	" 16, "	252	6.2
" 9, "	211	7.9	" 17, "	345	1.0
" 9, "	257	2.9	" 18, "	29	13.8
" 9, "	305	0.8	" 18, "	177	30.0
" 9, "	200	10.7	" 18, "	345	—1.5
" 9, "	316	0.9			
" 10, "	20	6.4			

The observations now recorded for nickel have been used in plotting the curves B and C in Figure 1. The nickel strip was, like the steel strip, so thin that the magnetic induction per square centimeter through it is assumed to have been the same as the strength of the field in which the strip was placed. Accordingly, the value of the magnetic induction is constant for each curve. The abscissas represent temperatures and the ordinates represent Hall effects. These ordinates for the nickel curves are reduced to the same scale as those for the steel curve; that is, the curves are an attempt to show how the Hall effects in nickel, with magnetic inductions 1500 and 3000, would compare in magnitude with those in steel, with magnetic induction 1400, if the strips were of the same dimensions and carried the same primary current.

Both of the nickel curves increase in steepness at first, but attain a maximum height between 150° and 200° and then fall very rapidly.

It is well known that certain marked changes occur in two of the physical properties of nickel in the region of 200° C. One of these is a thermo-electric effect, a reversal of the so called "specific heat of electricity" in the substance; the other is a great diminution of the magnetic permeability.

The "specific heat of electricity" is supposed to be nearly constant at temperatures below 200° C., and to suffer a second reversal of sign at a point somewhat above 300° C., in which two particulars it appears to have no connection with the course of the Hall effect at the same temperatures.

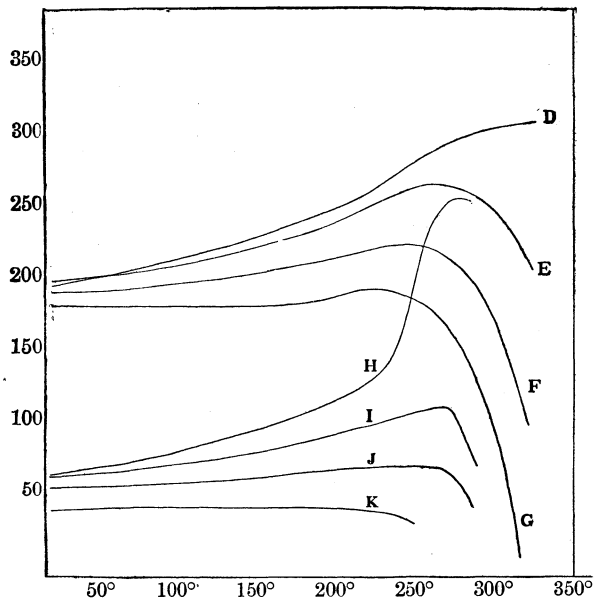


FIGURE 2.

In Figure 2 several curves are given to illustrate the changes of magnetic permeability, with unchanging magnetic induction, which nickel suffers with rise of temperature. Curves D, E, F, and G are plotted with data taken from the curves given by Mr. C. A. Perkins in the American Journal of Science, Vol. XXX. p. 218, to show how the magnetic properties of very pure rolled nickel are affected by changes of temperature. None of the curves given by Mr. Perkins

are directly available, for the reason that none of them are curves of constant magnetic induction. Curves H, I, J, and K are derived from curves given by J. Hopkinson, Royal Society Proceedings, June, 1888, p. 317, to show the effect of temperature changes on the magnetic properties of "an impure nickel." Hopkinson's own curves, like those given by Perkins, merely furnish data for these curves of constant magnetic induction, being either curves of constant temperature or curves of constant magnetizing force. From the history and description of the nickel specimens it seems likely that the nickel examined for the Hall effect resembled the nickel examined by Perkins more than it resembled that used by Hopkinson. The magnetic induction per square centimeter in the various cases is shown by the following table.

Curve.	Magnetic Induction.
B (Fig. 1.)	1,500
C "	3,000
D	1,500
E	2,000
F	2,500
G	3,000
H	500
I	1,000
J	1,500
K	2,500

An examination of curves D to K shows certain general resemblances. Most of these curves grow steeper with rising temperature, until a point lying between 200° and 250° is reached, then continue to ascend with diminishing steepness, and, attaining a maximum height before 300° is reached, afterward plunge suddenly downward. A similar statement holds true of the Hall effect curves B and C, as we have seen, but the turning points occur at considerably lower temperatures.

Some of the permeability curves in Figure 2 seem likely to cross the base line at temperatures between 300° and 400° , but experiment gives no warrant for such crossing, and there is much evidence in favor of continuing them as asymptotes to the base line. Curves B and C are probably asymptotic to the base line, although further experiments upon this point would not be superfluous.

In the group of curves D to G, as in the group H to K, it is evident that an increase of magnetic induction is accompanied by a lowering of the temperature of maximum permeability. In curves B and C it

appears that an increase of magnetic induction is accompanied by a lowering of the temperature of maximum Hall effect, but the number of observed points from which curve B is plotted is too small to warrant a conclusion upon this particular.

SUMMARY.

The Hall effect in copper and in phosphor-bronze is affected but little, if at all, by a rise of temperature from 20° to 360° C.

The Hall effect was about one half as great in the phosphor-bronze examined as in the copper, under like conditions.

The temperature coefficient of the electrical resistance of the phosphor-bronze appeared to be about 0.00045.

The Hall effect was observed in battery carbon.

In nickel there is on the whole, in spite of certain marked differences, a strong resemblance between the temperature changes of magnetic permeability and the temperature changes of that "rotative power" upon which the Hall effect depends. It is doubtful whether an equally strong resemblance as to temperature changes could be made out between either of these properties and any other property of nickel. An equally broad statement cannot as yet be made concerning iron or steel, but the evidence obtained, so far as it goes, is on the whole in favor of such a proposition.

NOTE. — ADDED MAY 19, 1893.

Wiedemann's *Annalen*, No. 3, 1893, contains an "Explanation of the Hall Phenomenon," by E. Lommel, which seems to me not well considered. Without reproducing Lommel's argument, which is easily accessible, I will make the following criticisms.

1. The "explanation" attributes to the supposed Amperian currents at the boundary of a magnetized body an entirely new power, in assuming them to increase the strength of an ordinary electric current within one half of the body and to decrease it in the other half.

2. If the Amperian currents in the boundary had the supposed effect upon the distribution of the current within the body, it is very doubtful whether this would produce the Hall phenomenon.

3. Lommel's conclusion is that the Hall effect has one direction in magnetic metals, and the opposite direction in diamagnetic metals. In fact, the direction in iron is opposite to that in nickel.

E. H. H.

NOTE. — ADDED JUNE 19, 1893.

Wiedemann's *Annalen*, No. 6, 1893, contains an interesting and important article by Professor Kundt on the "Hall Phenomenon in Iron, Cobalt, and Nickel." Taking exceedingly thin, transparent films of these metals, and subjecting them to the action of a magnetic field varying from a moderate intensity up to a value between 21,000 and 22,000 c. g. s., he has, with each metal, found the Hall effect and the rotation of the plane of polarization of light to maintain a constant ratio to each other throughout the whole range of magnetization. Then, depending upon the work of Du Bois (*Wied. Ann.* 31, 1887) for proof that the rotation of the plane of polarization of light in these metals is proportional to the *magnetization* ($\mathfrak{J}$) as distinguished from the *magnetic induction* ($\mathfrak{B}$), he concludes that in any given plate of iron, cobalt, or nickel the Hall effect is, other things being equal, proportional to the magnetization.

Professor Kundt credits me with having been the first to show the probability of a close connection between magnetization proper and the Hall effect in the case of nickel, but states that, in the case of iron and cobalt, "investigations hitherto have not gone beyond the limits within which the magnetization remains proportional to the magnetizing force." In this statement I think he does scant justice to some experiments of mine published in the *American Journal of Science* for August and October, 1888. These experiments, although they did not go far enough to put the matter absolutely beyond question, I felt to warrant me in making and publishing the following inference: "When a piece of iron, cobalt, or nickel is made to approach the state of 'magnetic saturation,' the transverse current [Hall effect] obtained from it increases somewhat less rapidly than the magnetic induction through the metal, but experiments with very highly magnetized iron and nickel indicate that this transverse current tends toward a fixed limit rather than a maximum followed by a decline."

The validity of Professor Kundt's conclusion that the Hall effect is *strictly proportional* to the magnetization, depends upon the validity of the law which Du Bois, as already stated, announced concerning the relation between magnetization and rotation of the plane of polarization of light. Now as this law was obtained by assuming for the thin transparent films of "galvanoplastic" nickel and cobalt used by Du Bois, the same magnetic coefficients found by Rowland in his famous rings of cast nickel and cobalt, and as, moreover, with this

assumption, the accordance between the calculated magnetizations and the observed rotations is far from strict, the law announced by Du Bois cannot be regarded as established beyond question.

If the law of Du Bois is strictly true, the strict proportionality between Hall effect and magnetization announced by Kundt must be held subject to the condition, *at a given temperature*. For numerous experiments, of which those in the paper to which this note is appended are the most extensive, have shown the Hall effect in the magnetic metals at ordinary temperatures to increase rapidly with rise of temperature, much more rapidly than the *magnetization* can be supposed to increase under the same conditions. In a very thin sheet of metal the relation between magnetization ($\mathfrak{J}$), permeability (μ), and intensity of magnetic field (which I will call F , and which in the case considered is practically equal to $\mathfrak{B}$, the magnetic induction) is

$$\mathfrak{J} = \frac{(\mu-1)}{4\pi\mu} F.$$

Now when μ is much greater than unity, as it is in all the magnetic metals at ordinary temperature and moderate magnetizations, it is evident that $\mathfrak{J}$ increases with rise of temperature much less rapidly than μ does. As to the rate at which μ increases with rise of temperature in the metals examined by Mr. Clough and myself, there is considerable doubt, but it is simply *impossible* for it to be great enough to make the magnetization $\mathfrak{J}$ keep pace with the Hall effect in the changes observed. The value of $\mathfrak{J}$ when $\mu = 20$ is $\frac{19}{80} \times \frac{F}{\pi}$.

Its value when $\mu = \infty$ is $\frac{1}{4} \times \frac{F}{\pi}$. Such considerations as this have

forced me to abandon the hope, which I once entertained, of making out for the relation between Hall effect and magnetization a law as simple as that which Professor Kundt has announced. It has long seemed, and still seems, to me that the only satisfactory method of studying that whole matter will be to repeat Rowland's experiments with carefully prepared rings from carefully chosen material, and then to work down slices of the same material to the proper shape and dimensions for exhibiting the Hall effect.

E. H. H.